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REVIEW ARTICLE

Recent Marine Geological Research in the Mariana and Izu-Bonin Island Arcs[1]

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ABSTRACT: Over the last decade models of the structure, composition, and evolutionary processes of the Mariana and Izu-Bonin island arc systems of the western Pacific have been changed profoundly by an interdisciplinary and multinational approach to studying the details of these regions. The standard marine geological studies have been superseded by detailed sea-floor mapping, sea-floor observations using submersibles, and deep-ocean drilling efforts. The increased level of effort is the result of discoveries of new geological phenomena in these regions and the desire to approach the study of ancient convergent margin terrains exposed on land in the light of the resultant insights. The new discoveries include active eruption of serpentine muds forming large volcano-like seamounts in the Mariana forearc, recent protrusion of serpentinite debris flows from fault-dissected horsts of metamorphosed supra-subduction zone mantle also in the Mariana forearc, similar ancient seamounts in the Izu-Bonin forearc region, evidence of recent forearc rifting, petrogenetically complex arc volcanoes situated within the backarc basin setting in both the Mariana and Izu-Bonin systems, the occurrence in close proximity to one another of magmas generated from different sources (the deep arc source and the shallower backarc basin basalt source) in neovolcanic zones of the incipient rifting portions of the Mariana and Izu-Bonin backarc rifts, and a variety of unique hydrothermal systems and fauna associated both with the arc volcanoes and with the active backarc spreading centers.

THE ACTIVE DEEP OCEAN trenches of the western Pacific mark the zones of collision and subduction between the Pacific lithospheric plate and the Asian continent. South of Japan this zone of collision takes place between the Pacific plate and the Philippine Sea plate, making interoceanic collision zones. The island arc systems generated in this region of the Pacific, the Mariana and Izu-Bonin arc systems, are of particular interest to marine geologists because such convergent plate boundaries provide an opportunity to study several fundamental processes of subduction in an environment uninfluenced by preexisting continental crust. In these relatively uncomplicated island arc systems it is simpler to decipher the components of the process of plate subduction and to study them. Only in this way can we begin to determine how these components are related to one another and how subduction relates to the evolution of the earth's lithosphere.

The physical effects of subduction on the wedge of crust and mantle overlying the descending lithospheric plate, in what is now termed the supra-subduction zone, are of particular concern to those interested in producing models of the nature of interactions between lithospheric plates. The type of model considered for each convergent margin depends on the subduction system. There are two end

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member types of convergent margins in the interoceanic settings, accretionary and erosional.

Accretionary systems are those in which portions of the down-going plate are detached, usually including part of the sedimentary column and sometimes part of the underlying igneous basement. These pieces of the subducting plate are then accreted as slivers, wedges, or en masse as exotic terranes onto the toe of the overriding plate. Erosional systems, such as the Izu-Bonin system, are those in which the toe of the overriding plate is mechanically eroded by normal faulting as the irregular surface of the down-going plate passes beneath it. Although it is generally accepted that both types of convergent plate margins currently exist within the ocean basins, there is growing acceptance of the concept that a given convergent margin may change from one mode to the other with time. A convergent margin may even exhibit both modes, varying with local environments along strike. Such a situation has been suggested for the Mariana system, which is erosional over most of its length, but is possibly accreting slivers of the Pacific plate in the southernmost latitudes. To understand the various factors that control the nature of subduction in any given convergence situation, a detailed model based on field evidence as well as theoretical considerations must be produced and tested.

Understanding the nature of the interactions between the subducted slab and the mantle through which it descends is critical for producing working models of subduction systems. Of obvious interest among these interactions is the generation of magmas in the supra-subduction zone environment and the formation of island arc volcanoes. Study of the evolution of the island arc volcanoes can document not only the timing of subduction and the structural evolution of the arc system, but also provide a means by which to trace aspects of the chemical interaction between the down-going plate and the supra-subduction zone mantle. The Mariana and Izu-Bonin systems are very different in the types of oceanic plates being subducted. The plate being subducted beneath the Mariana system contains numerous large seamounts. Thus, the composition of the plate is likely to be more heterogeneous on a small scale than is that of the seamount-poor plate being subducted beneath the Izu-Bonin system. Input to the Mariana arc system from constituents driven off the down-going plate may therefore be more heterogeneous.

The line of active volcanoes in the arc is known as the volcanic front. Behind the volcanic front, in many convergent margins, such as the Mariana and Izu-Bonin systems, rifting of the arc produces young ocean basins. As the basins evolve they progress from a series of rift graben to a system of volcanic rift segments offset by transform faults. The backarc basin regions of the Mariana and Izu-Bonin systems are particularly useful because they can provide information regarding the tectonic evolution of the backarc basins from the earliest stages of rifting (both Mariana and Izu-Bonin) to the more fully evolved (Mariana). The results of the tectonic studies of these two backarc environments are being compared with studies of continental rifting as well as with studies of midoceanic ridge rifting in an effort to contrast the rifting styles of convergent margin settings with those of purely divergent margin settings (the continental rifts and midocean spreading centers).

The backarc basins produce magmas that are similar to midocean ridge basalts in some regards, but have a unique compositional overprint from the arc that distinguishes them as a new class of basalt. Clearly, as the backarc basins evolve, the structural similarities to midocean ridges increase. If the magmas maintain a distinct composition, then even if the structural components of an exposed section through a backarc basin terrane appear to represent a midocean ridge setting, it would be possible to trace the origin of such an exposure to an arc environment. Geochemical studies of some subaerial suites of rocks that include oceanic sediments, basalts, gabbros, and associated mantle rocks (ophiolite sequences) show that these rocks formed in the supra-subduction zone environment, either in a volcanic front setting or in a backarc setting. Volcanological studies of the Mariana and Izu-Bonin arc volcanic fronts and backarc basin spreading centers provide the opportunity to investigate eruptive processes, both subaerial and submarine, and the generation of several types of economically valuable deposits, such as porphyry ore deposits, Kuroko-type deposits, and hydrothermal vent deposits.

Recently, attention has been drawn to a far less obvious locus for generation of magmas, the region trenchward of the volcanic front, termed the forearc. Located between the trench axis and the line of volcanic islands, the forearc region had long been considered too cold to permit the generation of magmas. Petrologists now recognize the importance of the evolution of magma types specific to the forearc environment (boninites, named for the Bonin Islands where they were first described) and have begun to provide detailed studies of their petrogenesis and distribution. To understand the process of magma production in the supra-subduction zone region, particularly in the forearc, we must investigate the distillation of the descending slab, the flux within the supra-subduction zone environment of the constituents driven off the slab, the associated metamorphism of the supra-subduction zone mantle and crust, and the secondary convection patterns set up by subduction that may serve to redistribute the distillates.

The dehydration of the down-going slab produces profound effects on the supra-subduction zone mantle. In the earliest stages of subduction the cooling effect of the down-going plate permits chemical changes in mineralogy of the supra-subduction zone mantle to proceed, producing low-temperature/high-pressure metamorphism. Once the subduction process has evolved to the point at which the Mariana and Izu-Bonin systems currently operate, the potential for metamorphism within the forearc is profound. Virtually the entire forearc region can be metamorphosed in the low-temperature/low-pressure to low-temperature/high-pressure ranges. This means that vast amounts of the constituents driven off the down-going plate can be accommodated within the supra-subduction zone mantle.

After two decades of increasingly more detailed investigations, the study of the Mariana and Izu-Bonin systems has burgeoned. The discoveries of actively erupting serpentine mud volcanoes in the Mariana forearc region; of uplifted blocks or protrusive diapirs of metamorphosed forearc mantle in both the Mariana and Izu-Bonin systems; of large, active backarc basin volcanoes erupting arc lavas; of the occurrence in close proximity to one another of magmas generated from different sources in neovolcanic zones of the incipient backarc rifting portions of both systems; and of active hydrothermal processes in the arc and backarc regions of both systems provided the impetus to perform in situ studies of these regions. A series of deep submersible (*Alvin*) dive cruises and two cruises of the Ocean Drilling Project were completed within the last two years in the Mariana and Izu-Bonin systems to study these new phenomena.

This paper documents these latest advances in marine geology of the Mariana and Izu-Bonin arc systems. It provides a technical summary of the development of ideas concerning the tectonic evolution of the arc systems and summarizes the major findings of the *Alvin* dive cruises and the drilling results.

Tectonic Setting

Early investigators of the Mariana and Izu-Bonin systems of volcanic and remnant arcs and backarc basins (Figure 1) provided a variety of evolutionary schemes to account for the current configuration of the major tectonic elements of the region. Uyeda and Ben-Avraham (1972) suggested that the Philippine Sea plate formed as a trapped piece of Kula/Pacific plate crust when reorientation of spreading occurred in the Pacific ca. 42 million years ago (mya). They further suggested that the subduction was initiated along a former transform fault offset some 1500 km and oriented roughly north-south between two east-west spreading center segments of the Pacific/Kula midocean ridge. Shih (1980) provided magnetics evidence that confirmed the entrapment hypothesis, but noted that the western Philippine basin drifted north ca. 15 to 20° and underwent clockwise rotation of about 50 to 70° since initial formation at about 40 mya. Klein and Kobayashi (1980) and Lewis et al. (1982) later suggested that the northern portion of the Philippine Sea plate, from the Oki-Daito ridge to the Palau-Kyushu ridge and the intervening basins, formed as a consequence of southward convergence, arc for-

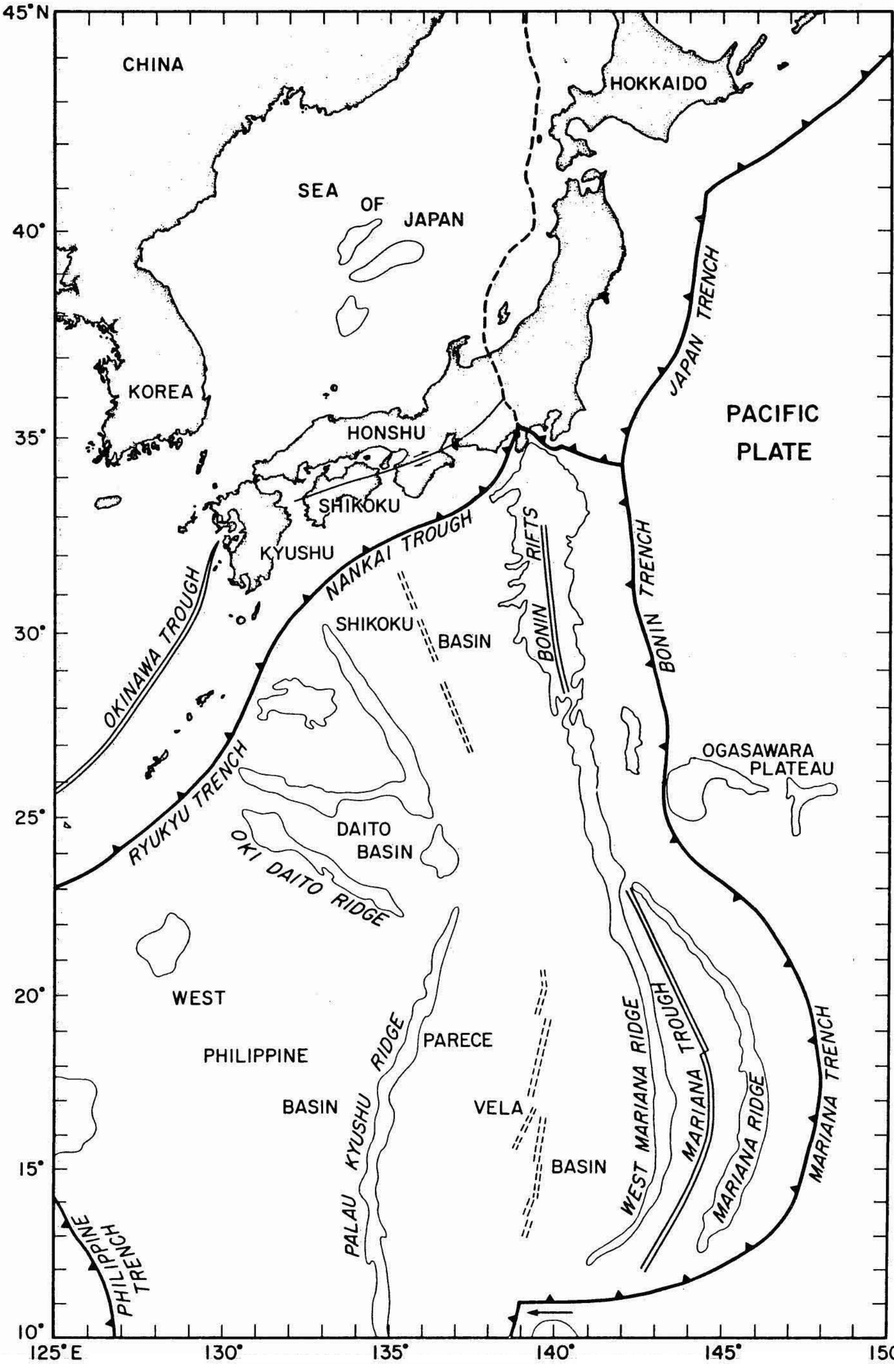

FIGURE 1. Location map showing major tectonic elements of the western Pacific in the vicinity of the Philippine Sea. Solid lines with solid triangles depict the axes of the trenches bounding the volcanic arcs and backarc basins of the region. Dashed double lines represent extinct spreading centers in the backarc basins. Narrow, solid double lines represent the axis of spreading in the active backarc basin—the Mariana Trough and the Bonin Rifts.

mation, and episodes of backarc rifting. They suggested that this region was moved northward as an integral part of the Philippine Sea plate during the translation/rotation episode. From ca. 21 to 15 mya the Parece Vela and Shikoku basins were opening, and the separation of the Mariana/Izu-Bonin arcs from the Palau-Kyushu remnant arc occurred (Scott et al. 1980). The opening of the Mariana backarc basin began at ca. 6.5 mya (Hussong and Uyeda 1981), and the initiation of the Izu-Bonin rifts probably began as recently as 1 mya (Brown and Taylor 1988).

The nature of the forearc regions, those areas between the volcanic front and the axis of the trench (Figure 2), has provoked considerable debate over the last two decades. The recognition that accretionary and erosional processes both can be active in supra-subduction zones and can produce vastly different types of forearc regions is a major advance in our understanding of the evolution of forearc terrains (Karig 1971, Hussong and Uyeda 1981, Karig and Ranken 1983, Fryer and Fryer 1987). Both the Mariana and Izu-Bonin forearcs seem to be primarily erosional. No large accretionary wedge has been noted in either of these forearc regions, and the results of studies of rocks collected from these areas indicate that they formed primarily of arc magmas (Skornyakova and Lipkina 1976, Detrich et al. 1978, Meijer 1980, Meijer et al. 1981, Wood et al. 1981, Bloomer 1982, Beccaluva et al. 1980, Bloomer and Hawkins 1983, Fryer et al. 1985*a*, Honza and Tamaki 1985, Ishii 1985, Fryer and Fryer 1987, Johnson et al. 1987, Saboda et al. 1987). Even in the deepest exposures of the inner trench walls the predominant rock type is an island arc basalt. Only very small volumes of alkalic basalts, presumed to be off-scraped fragments of oceanic islands, were noted in the samples recovered close to the inner wall of the Mariana trench (Bloomer and Hawkins 1983). Thus, it was suggested that the forearcs had been formed by arc volcanism and that the arc volcanics were exposed in the inner trench wall by tectonic erosion (Bloomer 1982). Recent dredge samples from the midregion of the Mariana forearc provide a different scenario. Basalts with trace element signatures of midocean ridge basalt (MORB) were collected from a deep fault scarp nearly 70 km from the trench axis (Johnson and Fryer 1988). The occurrence of MORB in these dredges requires a reevaluation of the existing models of evolution of the forearc regions. Further work will be required to determine whether these MORB lavas represent a fragment of old oceanic plate or indicate episodes of forearc rifting and generation of supra-subduction zone ophiolites. In addition to the arc volcanics, there are numerous exposures of ultramafic rocks in the outer portions of both the Mariana and the Izu-Bonin forearcs (Bloomer 1982, Fryer et al. 1985*a*, Ishii 1985, Bloomer and Hawkins 1987, Fryer and Fryer 1987). Large seamounts of serpentinite are forming over a zone ca. 100 km wide on the Mariana forearc (Fryer et al. 1985*a*, Hussong and Fryer 1985, Fryer and Fryer 1987), and older, sediment-draped seamounts are exposed on a narrow ridge on the inner trench wall of the Izu-Bonin system within 50 km of the trench axis (Honza and Tamaki 1985, Ishii 1985, Fryer and Fryer 1987). The origin of these seamounts, first described as serpentinite diapirs by Bloomer (1982), is currently under study. The seamounts vary from horst blocks of uplifted metamorphosed ultramafics to structures similar to mud volcanoes, but with far larger edifices, 20 km in diameter and 1500 m high. The nature of the active eruption of serpentine muds, the composition of associated fluids seeping through the vent systems, and the composition of the chimmey structures associated with the seeps are unique in the ocean basins (Fryer and Fryer 1987, Haggerty 1987*b*). The serpentinite seamounts provide an opportunity to study deep-seated processes of supra-subduction zone metamorphism and fluid flux. The mud volcano–like seamounts apparently entrain country rock from the walls of the conduit and thus sample deeper-level rock types than can be reached even by deep-sea drilling techniques.

In an effort to integrate existing geophysical and petrochemical data and to provide a regional geologic framework for studies of the detailed geology of the Mariana and Izu-Bonin arc systems, a series of 12 SeaMARC II side-scan sonar and bathymetry surveys was conducted in the Mariana and Izu-Bonin regions

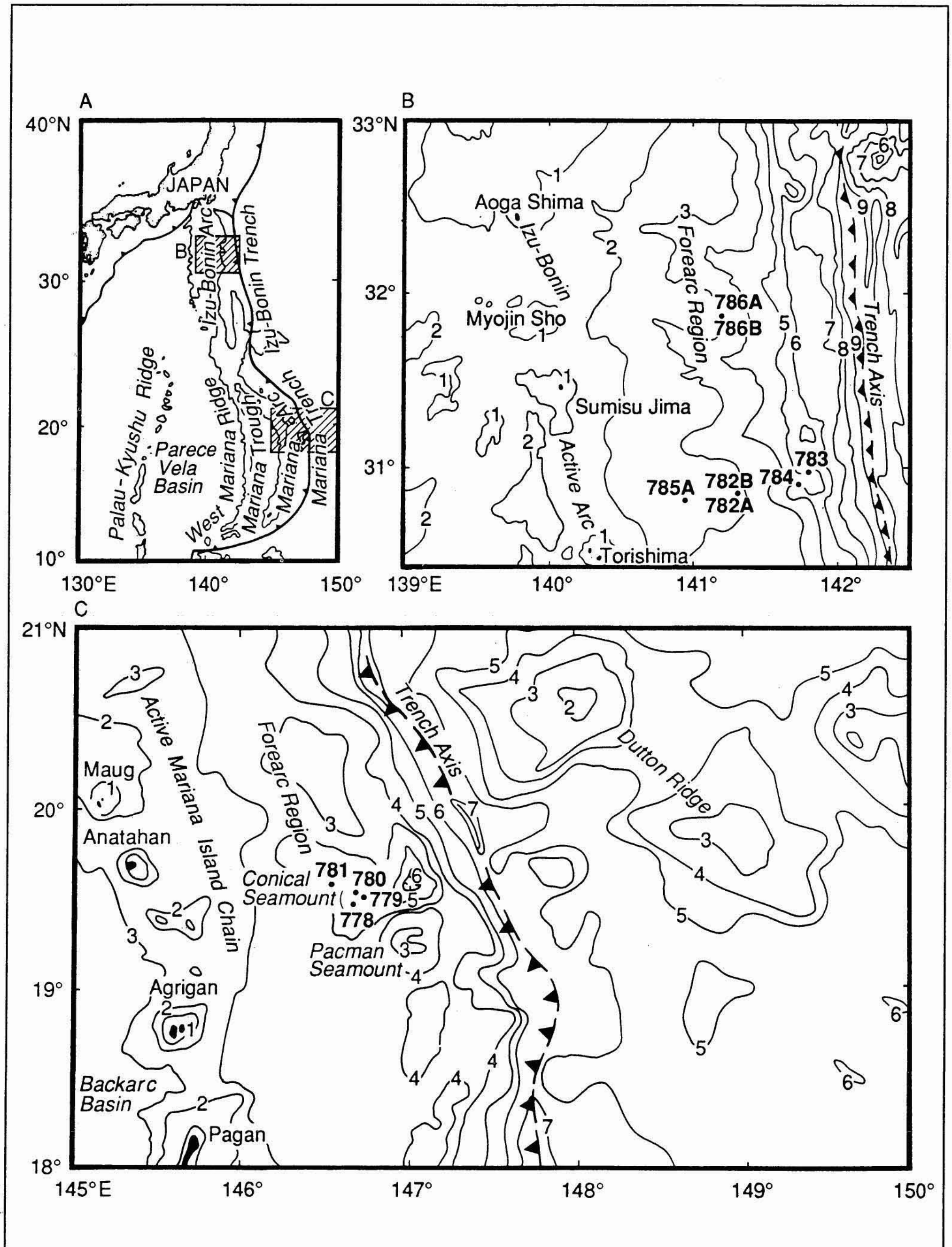

FIGURE 2. Maps of the major tectonic elements of the Philippine Sea region, the Mariana and Izu-Bonin arcs: *A*, a general locator map, showing locations of the detailed bathymetry maps (shaded areas) that are parts *B* and *C* of this figure (after Fryer and Pearce et al. 1989*b*); *B*, detailed bathymetry map of the Izu-Bonin forearc region contoured in 1000-m intervals, showing locations of Ocean Drilling Program (ODP) leg 125 drill sites; *C*, detailed bathymetry map of the Mariana forearc region contoured in 1000-m intervals, showing locations of ODP leg 125 drill sites.

over the past 8 yrs. The results of these surveys define neovolcanic zones in the northernmost Mariana backarc basin (Beal 1987) and in the Sumisu rift (Brown et al. 1988, Taylor et al. 1988). The surveys show the diversity of lava flow fields and structures associated with backarc spreading centers and arc volcanoes of the northern Mariana arc (Hussong and Fryer 1983, Beal 1987). In addition, the structural evolution of the innermost part of the northern Mariana forearc was investigated using side-scan and bathymetry data together with seismic reflection data (Mahoney and Fryer 1988) and indicated a recent change in stress regime in the northern part of the Mariana forearc. Structures there suggest that forearc rifting may play a significant role in the development of an arc system at any stage in its evolution. Investigations of the outer part of the Mariana forearc show the diversity of types of serpentinite seamounts (Hussong and Fryer 1985) and indicate the nature of the processes that favor their formation (Fryer and Hussong 1985, Fryer and Smoot 1985, Fryer et al. 1985*a*, Fryer and Fryer 1987).

With adequate background information and detailed field mapping accomplished, it was possible to design studies using the *Alvin* submersible and deep-sea drilling cruises to investigate specific aspects of the geological development of the Mariana and Izu-Bonin interoceanic arc systems. Specific details of the individual *Alvin* cruises may be found in Fryer et al. (in press *a,b*), Hochstaedter et al. (in press), Johnson and Fryer (in press), and Urabe and Kusakabe (in press). More comprehensive summaries of the drilling cruises may be found in Fryer and Pearce et al. (1989*a,b*) and Fujioka and Taylor et al. (in press).

Recent Alvin *Submersible Studies*

A series of six *Alvin* submersible cruises took place from April through August of 1987 in the Mariana and Izu-Bonin interoceanic arcs. The main objective of these cruises was to study in detail the geologic evolution of these arc systems of the western Pacific. The specific processes outlined for study ranged from active serpentinite diapirism in the forearc environment to active and incipient volcanism and hydrothermal activity in the arcs and in the backarc rift basins of these systems. The Mariana arc system was the primary focus of the dive cruises: five of them concentrated on the Mariana system. Three of the cruises dealt with petrology, tectonics, and hydrothermal systems of the Mariana backarc basin, the actively spreading, young ocean basin immediately west of the active islands of the Mariana arc. The first dives were on the active spreading center in the basin at about 18°13′ N (Figure 3). One cruise studied the serpentinite seamounts of the Mariana forearc. One focused on the volcanoes of the northern Mariana arc. One dealt with the arc and backarc volcanic centers of the central Izu-Bonin arc system, the Sumisu rift.

MARIANA BACKARC BASIN STUDIES AT 18°13′N. The first of the dive cruises to investigate the rift had been prompted by the discovery of $CH_4/^3He$ plumes in the water column 800 m above the sea floor (Horibe et al. 1986). The dives on the rift axis revealed a series of axial volcanoes and two large hydrothermal fields on the flanks of two of these volcanoes at depths of 3600–3700 m (Craig et al. 1987, Kastner et al. 1987). However, the vent waters are similar to those of Loihi Seamount (the active volcano immediately south of the island of Hawaii) vents in $^3He/^4He$ ratio (8.6 × atmospheric $[R/R_A = 8.6]$), with $CH_4/^3He = (0.5 \pm 0.2) \times 10^6$, and thus are very different from the plumes ($R/R_A = 3.2$, and $CH_4/^3He > 100 \times 10^6$) that had led to their investigation (Craig et al. 1987). Several smaller fields were discovered on the second dive cruise (Hessler et al. 1987). The hydrothermal vents were variable in terms of temperature, ranging from ~6°C to a maximum of 287°C. The high-temperature chimney structures produce "clear smokers" with vent water temperatures of up to 287°C in contrast to the "black smokers" (~350°C) that have been discovered on midocean ridge hydrothermal systems (Campbell et al. 1987). The structures are dominantly composed of barite and silica, but also contain spalerite, galena, and minor chalcopyrite (Craig et al. 1987, Kastner et al. 1987). As compared with midocean ridge vents of similar temperatures, the composition of the

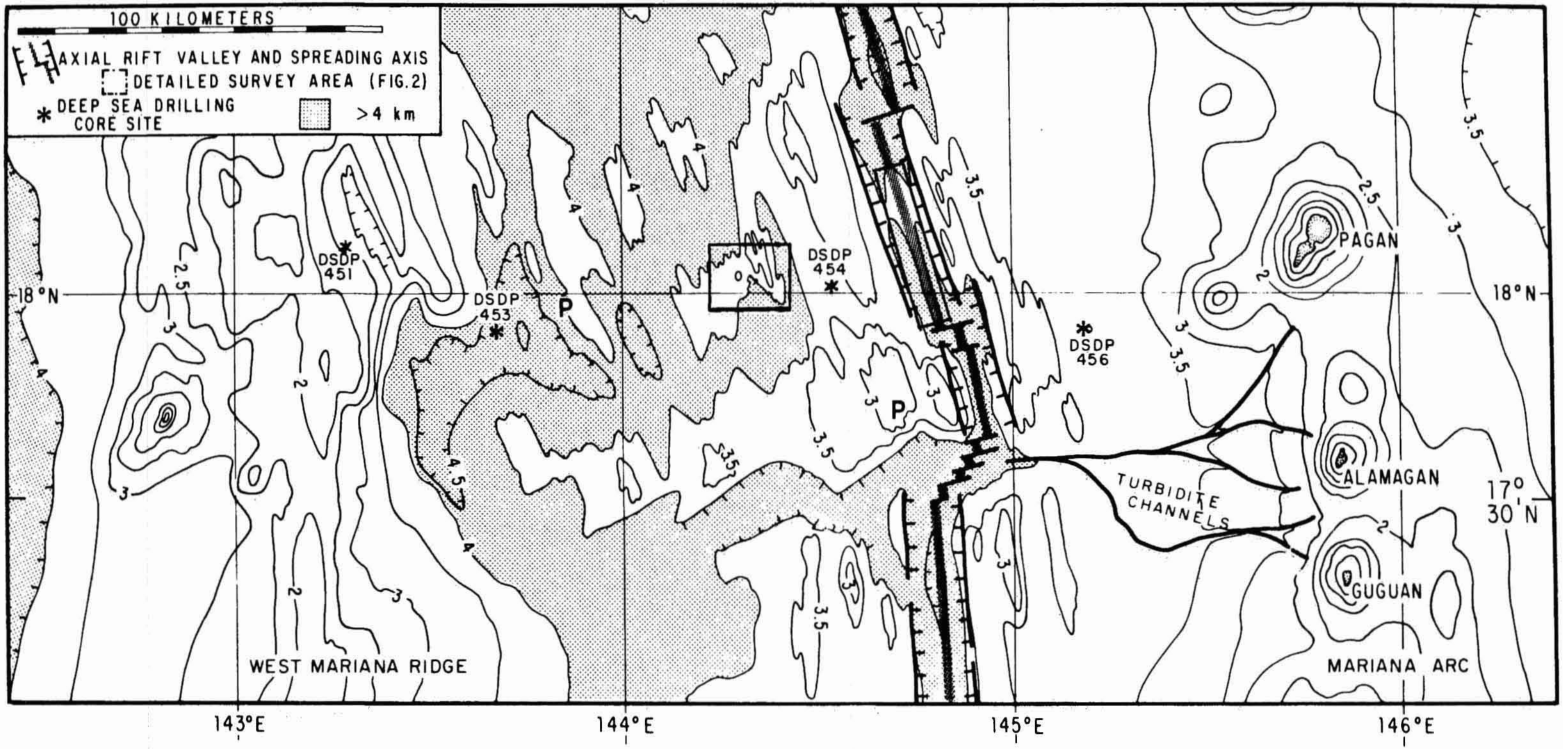

FIGURE 3. Bathymetry map of the central part of the Mariana backarc basin contoured in 500-m intervals (after Lonsdale and Hawkins 1985), showing location of the spreading ridge (dark hatchured lines), locations of Deep Sea Drilling Project (DSDP) leg 60 drill sites, and locations (boxes) of the *Alvin* dive regions on both the Mariana backarc basin spreading center (*right*) and on the off-axis, hydrothermal mounds area (*left*). Depths greater than 4000 m are shaded.

Mariana vent fluids and chimney structures is different from those of hydrothermal regions on midocean ridge spreading centers (Campbell et al. 1987, Kastner et al. 1987). The pH of the water samples from the Mariana high-temperature vents is 4.39 compared with 3.8 for midocean ridge vent fluids, and the alkalinity of the Mariana vent waters is also higher, 0.43 meq/l compared with -0.19 meq/l for midocean ridge vent waters (Campbell et al. 1987). Boron in the vent waters of the Mariana chimneys is 200% that of ambient seawater and has a $\delta^{11}B$ of +20/mil, whereas midocean ridge vents are usually only 10 to 20% enriched relative to seawater, with a $\delta^{11}B$ of +26 to +32/mil (Campbell et al. 1987). It appears from both composition of the chimney structures and from the composition of the Mariana vent fluids that precipitation of sulfides must be occurring at depth within the ridge crest hydrothermal system, although no samples of such precipitates were recovered (Campbell et al. 1987, Kastner et al. 1987).

Biological studies of these vents were planned in an attempt to characterize for the first time the detailed nature of vent communities in the western Pacific. The vent fauna associated with these fields is described by Hessler et al. (1987) as rich and unusual. Depending on the temperature of the fields, the fauna of the communities varies. The low-temperature (~6°C) regions are characterized by abundant widespread anemones and clusters of barnacles around discrete vent openings. Associated with the barnacles and anemones are galatheid crabs and polynoid polychaetes. The fields with slightly higher temperatures (from ~15°C to 250°C) contain clusters of a unique "hairy" gastropod around the vents, grazing bresilid shrimp and brachyuran crabs, encrustations of barnacles, paralvinellid polychaetes and associated harpactacoid copepods, many limpets, occasional mussels, and dispersed anemones.

The second dive cruise on the spreading axis provided structural and petrologic studies of the rift center volcanoes. These studies are extensions of deep-tow surveys, multibeam studies, and dredging work that had been performed before the diving cruise (Lonsdale and Hawkins 1985, 1987). The details of the structural variation in the volcanic centers are an important component in the interpretations of both the distribution of the hydrothermal fields and the petrogenesis of the lavas recovered during the dives. Thus, as a consequence of the second dive cruise the structure of the rift volcanoes and relationships of the structure to the petrology of the lavas distributed along the rift were integrated with more detailed investigations of the hydrothermal fields. The dives confirmed the remarkable variation in structure along the rift that had been discovered by multibeam surveys (Hawkins et al. 1987). A total of 18 *Alvin* dives augmented by 26 dredges detail the composition of the basalts and more evolved lavas that were erupted from the largest edifices (Hawkins et al. 1987). The lavas have a source similar to that of MORB based on the major element compositions (Hawkins et al. 1987). This observation confirms earlier work based on dredge and deep-sea drilling samples (Fryer et al. 1981, Wood et al. 1981, Sinton and Fryer 1987), but provides far greater detail in terms of distribution of various rock types along axis. Isotopic analyses and the Rb and Sr concentrations of the basaltic glasses from some of the samples confirm an intimate mixing of the MORB source with an arclike source component (Macdougal et al. 1987) on a scale not discernable with analytical results from dredge samples (Sinton and Fryer 1987). Thus, the geochemical results from the *Alvin* studies provide a far more detailed examination of the relationships of the petrology to the structure of the spreading center.

The last of the Mariana backarc basin dive cruises (the fourth cruise to the Mariana region) concentrated on the hydrothermal systems occurring off-axis in the central latitudes of the basin. Detailed studies of fields of off-axis hydrothermal mounds, discovered by heat-flow and deep-tow studies (Leinen and Anderson 1981, Hobart et al. 1983, Lonsdale and Hawkins 1985), their structure, sediment composition, associated heat flow, pore water composition, nutrient profiles, and pore pressures were the focus of the *Alvin* dives in the mounds area (Leinen et al. 1987, Wheat and McDuff 1987). The mounds, located ca. 50 km west of the Mariana backarc rift center, show high heat-flow values exceeding 10 watts/m, and nonlinear concave thermal gradients indicate an active hydrothermal system, recharge of the system, and potential escape of fluids along fault scarps within the region (Leinen and Anderson 1981, Hobart et al. 1983, Leinen et al. 1987). The mounds occur in regions of high heat flow that are located in several semilinear depressions oriented roughly north-south along a north-south trending ridge. The mounds vary in morphology from smooth to pockmarked to hummocky features 1 to 2 m high. The heat flow within the mounds area was monitored by the first in situ long-term heat-flow monitor and was found to fluctuate over a period of 10 days at the vent of the mound studied, but smoothly decreases exponentially away from the mounds (Leinen et al. 1987, Yamano et al. 1987). Investigations of the nutrient profiles within the areas of high heat flow and of the physical properties of the sediments collected in push cores from the mounds add information critical to the understanding of the hydrothermal system active in the mounds area. Nutrient profiles from piston core data correlate directly with the pattern of heat flow and show generally higher nitrate (constant with depth) and silicate (constant or decreasing with depth) concentrations than bottom water and that phosphate concentrations decrease or remain consistently lower than 1 microMolar, whereas in areas of low heat flow silica and phosphate concentrations increase and nitrate concentrations decrease with depth (Wheat and McDuff 1987). Increasing porosity with depth in the piston cores suggests that the pore water advection driven by the hydrothermal system disrupts processes of normal sediment consolidation (Dadey and Leinen 1987). Previous studies of sediments from the area revealed hydrothermal mineralization similar to that encountered in off-axis mounds in the Galápagos region (Leinen and Anderson 1981). However, none of the sediments reported from the *Alvin* dives show chemical alteration similar to that encountered in the Galápagos mounds (Leinen et al. 1987). The earlier studies of Lonsdale and Hawkins (1985) indicated that the mounds area is complicated by an episode of silicic volcanism, which they suggested indicated incorporation of sediments into igneous melts, subsequently superimposed on a backarc basin basalt substrate. The distribution of the areas of high heat flow and the associated mounds appeared to be controlled by faulting, not by evenly disseminated hydrothermal activity (Leinen et al. 1987). The mounds are structurally complex and associated heat-flow values indicate variability even within a given mound. The vertical pore pressures measured in in situ measurements were the highest ever measured in hydrothermal mounds in the ocean basins. The distribution of the mounds and the local topography confirm the structural control over the formation of the mounds (Leinen et al. 1987).

MARIANA FOREARC STUDIES. Serpentinite seamounts in the Mariana forearc region have been particularly well studied at 19°30′ N, 147° E (see Figure 2). There, side-scan and bathymetry surveys and the results of petrologic and geochemical studies reveal the presence of two distinct forms of serpentine seamounts (Hussong and Fryer 1985, Fryer and Fryer 1987). These two edifices were the sites of dives on the third *Alvin* cruise in the western Pacific. A young, actively erupting serpentinite seamount, informally named Conical Seamount, lies at the intersection of several fault lineaments at the edge of a large forearc graben (Newsom and Fryer 1987). It is similar in appearance on side-scan imagery to a mud volcano, the flanks of which are covered with long sinuous flow forms. An apparently older, possibly diapiric seamount or uplifted horst block of serpentine, informally named Pacman Seamount, is situated to the southeast of Conical Seamount. Pacman Seamount is cut by east-west trending faults and is breached on the east flank by a fault-bounded collapse graben. This eastern-flank graben is partially filled by a large oval-shaped flow of serpentinite debris. The objectives of the dives on these seamounts were to investigate the upper flanks of the seamounts in the vicinity of flow features observed on side-scan images and to study what active processes occur at the summit of the seamounts, to sample the flow material and any chimney material that might be present on the seamounts, and to determine the composition of vent fluids associated with the seamounts.

Eleven dives were completed on these two seamounts. The dives explored the serpentine flows on the flanks of Conical Seamount and the faulted southern flank. The rock types recovered in dives and dredges from the flanks of the seamounts reveal a variety of metamorphosed crustal and upper mantle rocks (Saboda et al. 1987). The dredge hauls on the fault scarps surrounding the large forearc graben east of the seamounts have revealed the first evidence for MORB composition lavas in a forearc setting (Johnson and Fryer 1988). The fault scarp from which these MORB-like basalts were retrieved is ca. 2000 m high and exposes the MORB-type basalt at high levels in the outcrop. Thus, the MORB lavas are not deeply buried under an arc-generated carapace, as would be expected if the models of formation of the supra-subduction zone lithosphere in the Mariana forearc as previously espoused are correct. Furthermore, although most of the basalts from Conical Seamount have island arc trace element characteristics, some also have trace element signatures of MORB. This indicates that the presence of MORB-type lavas can be traced over a region at least 40 km wide in the vicinity of the area studied. The variety of rock samples, ultramafic to mafic, collected from the dive and dredge sites is further confirmation of the high degree of tectonic deformation in the Mariana forearc and of the degree of faulting associated with formation of serpentinite seamounts (Fryer and Fryer 1987). At the summit of Conical Seamount the dives revealed recent flows of unconsolidated serpentine devoid of sediment cover. In a small region (ca. 100 m in diameter) on the west side of the two summit knolls, chimney structures composed of both carbonate and silicate (Fryer et al. 1987*b*, Haggerty 1987*b*) were discovered. The chimneys varied in morphology from a corroded appearance in the carbonate (aragonite and calcite) chimneys to a smooth appearance in the silicate chimneys (composed of a new mineral, a Mg-silicate analogous to allophane [Haggerty 1987*b*, Haggerty and Cloutier 1988]). Small limpets, gastropods, and bacterial mats were collected from the chimneys. Twenty-two bacterial isolates were produced from the samples of the chimneys, and studies of their possible genetic interrelationships to the chimneys are in progress (Cloutier and Haggerty 1988, Haggerty and Cloutier 1988). Fluids actively seeping from one of the chimneys were sampled at the active silicate chimney and revealed an unusual chemistry. The pH of the fluids is high (9.28 versus 7.72 for ambient seawater), alkalinity is also high (5.53 versus 2.41 meq/l), and the vent waters are enriched in CH_4 (1000 versus 2.1 nM), SiO_2 (0.75 versus 0.12 mM), SO_4 (30.4 versus 28.6 mM), and H_2S (2.1 mM versus not detected in ambient). Note that seawater probably mixed with the fluids during sampling, because the rate of seepage from the chimney is very slow. Thus, these enrichments must be considered minima. The enrichments noted imply that deep-seated serpentinization processes as well as interaction of seawater with crustal rocks and interactions of seawater with the surficial serpentinite may all contribute to the composition of the fluids. The deep-seated origins of the fluids are substantiated by work on similar chimney samples collected from a dredge of a serpentinite seamount in the southern portion of the Mariana forearc. The isotopic C and O composition of the southern seamount chimney samples indicates that a source other than seawater is involved in the generation of the fluids (Haggerty 1987*a*). Fluid inclusion work performed on aragonite needles from the *Alvin* samples from Conical Seamount and from the southern seamount dredge samples indicates the presence of methane and higher hydrocarbons, the sources for which are probably deep-seated within the supra-subduction zone (Haggerty 1989).

Dives on Pacman Seamount explored the large oval-shaped flow of serpentine that partially fills the graben on the seamount's eastern flank, the summit region of the seamount, and the faulted portion of the southern upper flank. Pacman Seamount showed no signs of recent activity, and no chimney structures were observed on the summit dive. The upper half of the fault scarp on the southern margin of the flank graben on the eastern side of the seamount exposes massive serpentinite with blocky morphology and no flow matrix material. Thus, the interior of this portion of the seamount is probably massive serpentinized ultramafic rock exposed by normal faulting within the forearc. Pacman Seamount shows no evidence of being composed of layered flows of the kind observed on Conical Seamount.

The results of the Mariana forearc dives provide clear evidence that the serpentinite seamounts can be formed by a variety of processes, that they occur in association with large-scale faulting on the forearc, and that the serpentinite probably originated from the supra-subduction zone mantle. Also it is clear that fluids emanating from the active Conical Seamount are at least in part of deep-seated origin and that the serpentinite flows have entrained crustal-level basalts during emplacement. These seamounts differ from serpentinites of midoceanic fracture zones in the chemistry of authigenic minerals with which they are associated (Haggerty 1987*a*) and in their manner of emplacement (Fryer and Fryer 1987). They likely provide in situ examples of processes that are analogous to those that have formed serpentinite deposits and structures noted in subaerial exposures of convergent margin terranes in numerous locations worldwide (Lockwood 1971, Carlson 1984).

MARIANA ARC VOLCANISM AT 22° N. The volcanoes of the northern part of the Mariana arc (Figure 4) are of interest for two primary reasons: volcanism in the northern portion of the arc-backarc region is most likely to have been influenced by the recent rifting of the arc (Stern et al. 1985, Bloomer et al. 1989, Lin et al. 1989); and the northern volcanoes show increasingly alkalic compositions, reaching shoshonitic rock types north of 23° N. The alkalic compositions are suggested to indicate an incipient rifting environment. Structurally the northern portion of the arc is of great interest because the whole of the forearc and arc region apparently has been subjected to some degree of both cross-arc rifting and forearc extension (Hussong and Fryer 1983, Beal 1987, Fryer et al. 1987*a*, Mahoney and Fryer 1988). Two large chains of well-

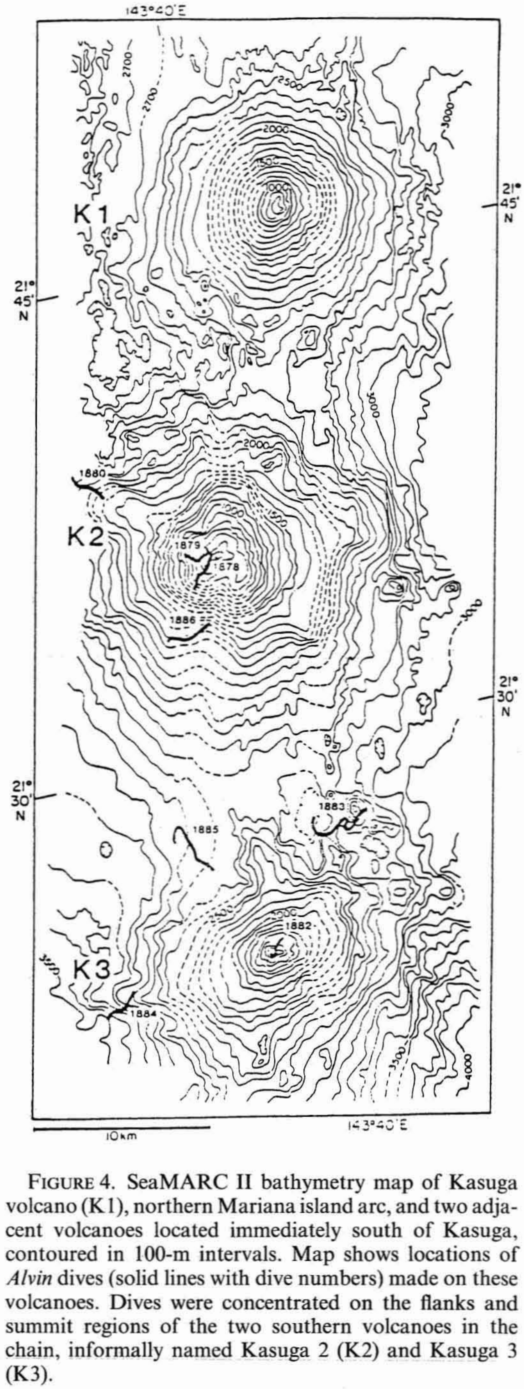

FIGURE 4. SeaMARC II bathymetry map of Kasuga volcano (K1), northern Mariana island arc, and two adjacent volcanoes located immediately south of Kasuga, contoured in 100-m intervals. Map shows locations of *Alvin* dives (solid lines with dive numbers) made on these volcanoes. Dives were concentrated on the flanks and summit regions of the two southern volcanoes in the chain, informally named Kasuga 2 (K2) and Kasuga 3 (K3).

developed, large volcanic edifices are located in the northern portion of the backarc basin, extending from the arc line for 60 km into the backarc basin. The northernmost of these two, the Kasuga chain, extends onto the rift axis region (Beal 1987). The Kasuga volcanoes were initially studied by SeaMARC II surveys and dredging (Hussong and Fryer 1983, Beal 1987, Jackson 1989). The structural complexity of the edifices is evident on the side-scan sonar imagery. There are numerous lava flow fields and regions mantled with volcaniclastic debris on the two southernmost of the three volcanoes imaged (Hussong and Fryer 1983). Dredge results show typical backarc basin lavas on the lowest slopes of the second volcano in distance from the active arc (Kasuga 2) and basalt to andesitic lavas with variable K content (ranging from $<1\%$ to $>2\%$ with $Na_2O/K_2O < 1$) (Jackson 1989). Basalts and hornblende-bearing dacites were dredged from the summit region of the third volcano in distance from the arc, Kasuga 3. Magma mixing processes are evident in the composition of the summit lavas from both volcanoes. The freshness of the lavas recovered and the presence of active hydrothermal systems suggest that these seamounts are active. The volcanoes were probably built on backarc crust after a recent cross-arc rifting event, and the magmas from which they were constructed were probably derived from at least two separate sources, a backarc basin basalt source and an arc source. The *Alvin* dive cruise to these volcanoes and additional bottom photography work and dredging confirm the complex interrelationships of magma sources that had been seen in the dredge samples (Jackson 1989). Samples collected on the *Alvin* dive cruise further document diversity of lava types on the lower flanks of the volcanoes (Jackson et al. 1987, Jackson 1989). Hydrothermal systems were discovered on the summits of the two volcanoes on which the dives were conducted (Vonderhaar et al. 1987). A boiling system was identified on Kasuga 2. Hydrothermal fluids collected from the Kasuga 2 field have an unusually high and as yet enigmatic Mg content (McMurtry et al. [in press]). A large volcaniclastic debris deposit mantles the southern flank of Kasuga 2, and observations of the upper half of the deposit indicate that it may have been emplaced hot in the submarine environment. Large boulders originally up to 2 m in diameter were observed on the surface of the deposit. These had apparently decrepitated, and they, as well as smaller, unbroken boulders, were encrusted on their lower surfaces with hydrothermal deposits. A comparison of the small grain-size fraction of this deposit with that of Kick-em-Jenny Volcano of the Lesser Antilles arc shows remarkable similarity (Ballance et al. 1988).

SUMISU RIFT, IN THE IZU-BONIN ARC SYSTEM. The Izu-Bonin backarc region at about 31° N (Figure 5) is undergoing the earliest stages of backarc spreading (Brown and Taylor 1988). The rift grabens in the area are deeply sedimented with hemipelagic and volcaniclastic sediments. However, there are numerous active volcanic centers, generally erupted along either arc-parallel normal faults or along transfer zones within the rift basins, and regions of high heat flow (up to 600 mW/m^2) within the grabens that attest to the recent volcanic activity (Taylor 1987). Several of these neovolcanic zones were investigated during an *Alvin* cruise, augmented by detailed SEABEAM and bottom camera surveys (Taylor 1987). The objectives of the cruise were to investigate the structure, petrology, and geochemistry of both igneous materials and hydrothermal deposits associated with volcanism on the backarc rift centers. Previous side-scan sonar studies and dredging of the central rift region showed the Sumisu region at 31°05′ N to be dominated by an enechelon ridge with a right lateral offset (Brown and Taylor 1988, Brown et al. 1988, Taylor et al. 1988). Most of the lavas dredged from the ridge are backarc basin basalts, similar to MORB, but with an overprint of an arc component (Fryer et al. 1985*b*, Fryer et al. in press *b*). Similar lavas were also recovered from the base of the fault scarp bounding the eastern side of the Sumisu rift. The presence of typical backarc basin basalt so close to the active arc indicates a separate magma source in close proximity to the arc magma source. Petrologic studies indicate a shallower source of melting to form the backarc basin basalts of

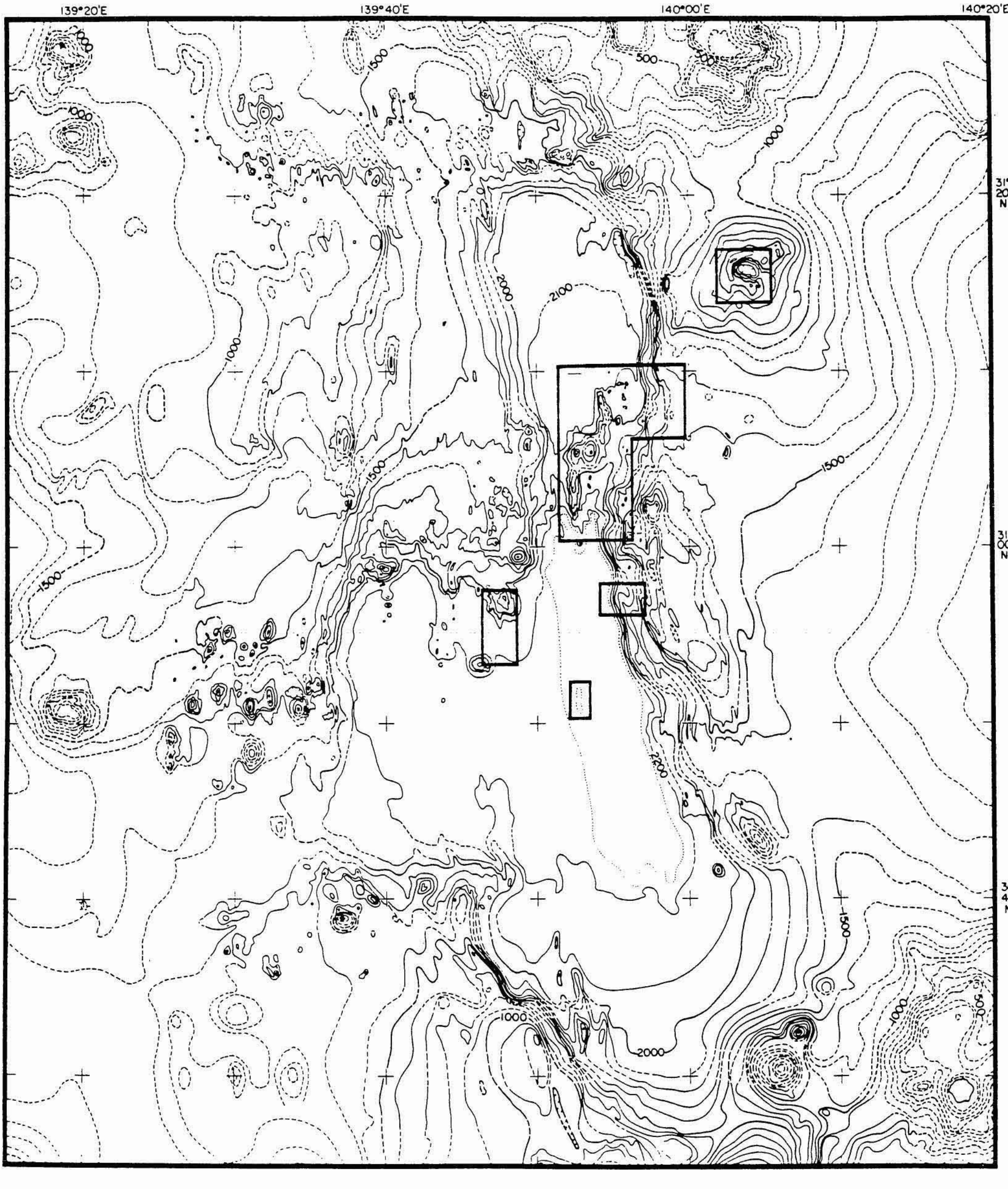

FIGURE 5. SeaMARC II bathymetry map of the Sumisu rift contoured in 100-m intervals, showing locations (boxes) of the regions investigated with *Alvin* (after Smith 1989).

the Sumisu rift (Fryer et al. [in press *b*]). At the offset region between the northern and southern segments of the ridge, samples of both basalt and silicic (dacite and rhyolite) lavas were recovered (Fryer et al. 1985*b*, Fryer et al. [in press *b*]). The results of the dive series confirm the previous petrologic findings and provide a detailed petrogenetic model based on stratigraphy and clearly defined spatial distribution (Hochstaedter et al. [in press]). Hydrothermally generated barite-silicate chimney materials were discovered on the large edifice centered on the offset region and along the southern portion of the northern arm of the enechelon axial ridge (Urabe and Kusakabe [in press]). The hydrothermal deposits are suggested to be products of Kuroko-type environments, and the Sumisu rift represents a likely site for the in situ study of the kind of high-grade ore generation typical of Kuroko deposits. A return to the Sumisu rift region in the summer of 1989 with the Shinkai 2000 submersible (operated by JAMSTEC) provided additional evidence for the widespread occurrence of barite-silica hydrothermal chimney deposits in the northernmost part of the southern arm of the Sumisu ridge (A. Malahoff, 1989, pers. comm.).

Recent Ocean Drilling Project Studies

Several deep-sea drilling cruises have been conducted in the Philippine Sea area, concentrating on the evolution of the Mariana and Izu-Bonin arcs and their backarc basins. Deep Sea Drilling Project legs 31, 58, 59, and 60 studied the evolution of the Philippine Sea, the Parece Vela Basin, the Shikoku Basin, and the Mariana island arc system. Summaries of the results of these drilling studies are presented by Karig (1975), Klein and Kobayashi (1980), Scott et al. (1980), Natland and Tarney (1981), and Hussong and Uyeda (1981). With the exception of leg 60, these early drilling cruises focused on the evolution of the backarc basin settings and on the composition of the ancient remnant volcanic arcs associated with them. Leg 60 also investigated the active arc and the forearc of the Mariana system.

Recently, Ocean Drilling Project legs 125 and 126 studied the Mariana and Izu-Bonin forearc regions and the Sumisu rift (Fryer and Pearce et al. 1989*a*,*b*, Fujioka and Taylor et al. [in press]). On leg 125 four sites in the Mariana forearc and five sites in the Izu-Bonin forearc provided the first look at the interior of forearc serpentinite seamounts, allowed documentation of the volcanic basement and its sedimentary history, and revealed the first evidence of recent volcanism in an active supra-subduction zone. The interior of Conical Seamount is composed of convoluted serpentinite flows bearing clasts of metamorphosed ultramafic to mafic rocks. The mafic rocks are of both island arc and midocean ridge compositions. Pore fluids from the serpentine mud flows have compositions even more dramatically different from that of seawater than those observed seeping from the chimney structure studied with *Alvin* (Fryer and Pearce et al. 1989*a*,*b*). The summit region of the seamount was confirmed to be actively venting fluids and to be producing serpentinite flows through what is interpreted to be a summit conduit system. Also confirmed was the deep-seated origin and the high hydrocarbon content of the associated fluids (Fryer and Pearce et al. 1989*a*,*b*). Drilling at the site on the lowermost west flank of Conical Seamount intersected a Pleistocene basalt lava of island arc composition (Fryer and Pearce et al. 1989*a*,*b*), thus placing in question the current models of thermal structure of and magma genesis in supra-subduction zones. Drilling at two lower flank sites on Torishima Forearc Seamount, a serpentinite seamount on the Izu-Bonin forearc, revealed serpentinite flows similar to those on Conical Seamount beneath the sediment cover. However, in contrast with the active Conical Seamount, the Torishima Forearc Seamount was formed some 10 mya and is apparently no longer a source of serpentinite debris or mud flows (Fryer and Pearce et al. 1989*a*,*b*). Three sites in the Izu-Bonin forearc sediments revealed a history of volcanism from Eocene to Recent with peak periods in the Eocene-Oligocene and Miocene to Pleistocene (Fryer and Pearce et al. 1989*a*,*b*). The last site drilled penetrated deep into a Middle Eocene ($\sim$42 mya) volcanic center, documenting the oldest volcanism yet recovered from either the Mariana or Izu-Bonin forearc. The age of the microfossils associated with the lavas and the composition of many of the lavas and underlying dikes (boninitic) are consistent with the formation of this volcanic center during the earliest stages of subduction within the Mariana and Izu-Bonin systems. Thick sequences of pelagic/volcaniclastic sediments were drilled in the forearc on leg 126, documenting Oligocene through Pleistocene volcanism on the arc, and backarc basin sites were drilled revealing rapid sediment accumulation and the nature of the basement volcanics of the Sumisu rift (Fujioka and Taylor et al. [in press]).

Summary and Conclusions

Profound changes in the models of arc evolution have resulted from recent studies of the Mariana and Izu-Bonin interoceanic arc systems. These arcs are now accepted as having formed primarily by tectonic erosion, not accretion. Their forearc regions are recognized as having migrated north considerable distances since the Eocene. Furthermore, it is acknowledged that the forearcs have experienced small-scale rotation, vertical deformation, and episodes of rifting in response to plate adjustments, subduction of plate seamounts, and collisions of the arc with large aseismic ridges on the oceanic plate. Vast portions of the supra-subduction zone have been subjected to metamorphism driven primarily by fluid flux through that region in response to dehydration of the subducted oceanic slab. It is likely that the large amounts of fluid hypothesized to have been driven off the slab over the last 40 million years could be completely accommodated by that metamorphism and by the type of escape of fluids observed at Conical Seamount. Thus, the problematical imbalance between the volume of fluid derived from the slab and the comparatively small amount of volatiles measured in arc-generated lavas can be resolved. The wide variety of rock types recovered from the Mariana and Izu-Bonin forearc and the discovery of ancient volcanic centers and recent basalts require us to reevaluate our concepts of the petrogenetic evolution of the forearc crust and mantle. The presence of metamorphosed mantle rocks in great abundance in the outer portions of the forearcs will only be fully understood with more detailed study of their composition, distribution, and relationships to structural features of the forearcs.

The study of the arc lavas of the northern Mariana arc, the Mariana backarc basin, and the Sumisu rift in the Izu-Bonin backarc region provides the means by which to understand the interaction between arc-generated lavas and the backarc basin basalts. This interaction is a tracer of the tectonic evolution of the backarc basin systems. The apparently shallow-generated backarc basin basalts are emplaced in remarkably close proximity to true arc-generated lavas. Volcanoes of the backarc basins are composed of lavas of a wide range of compositions and support a variety of types of hydrothermal systems. Although analogies to the kinds of hydrothermal systems found on the midocean ridges can be drawn, those of the backarc basin spreading centers have a unique composition reflecting influence of the adjacent arc environment. Even the vent fauna associated with these systems is in some instances unique.

The importance of understanding these regions is becoming increasingly evident as more and more ophiolite terrains are identified as having formed in an arc environment. Serpentinite terrains, previously thought to have formed during obduction episodes or to be exposures of ancient transform faults, are now being recognized as having similarities in structure and composition to those described from the Mariana system. Thus, the comparisons of subaerial terranes to the recent studies of the interoceanic convergent margins will continue to add immeasurably to our understanding of plate interactions and the evolution of the volcanic arcs and backarc basins generated within such environments.

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